Upstream LNG Technology

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Lecture – 38
Tutorial on ideal binary distillation

Welcome. Today, we shall do some calculation on the ideal binary separation by distillation about which we have learned the theory earlier.

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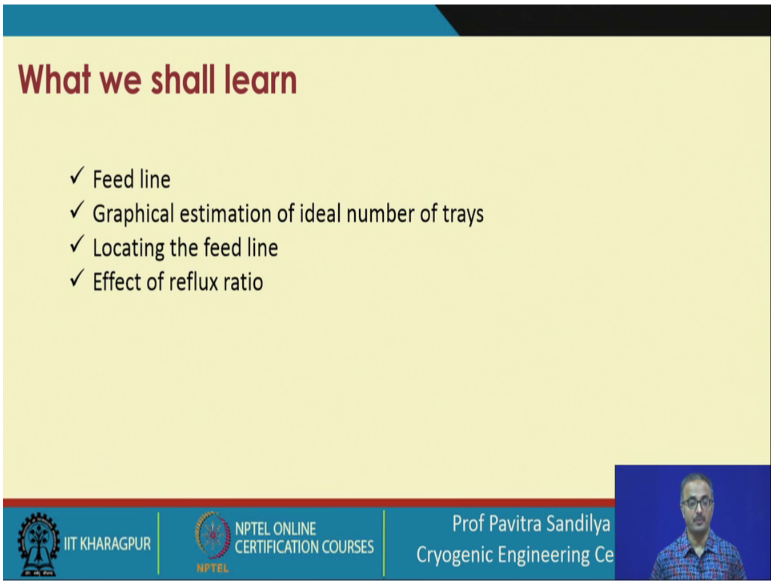

So, in this particular tutorial, what we shall learn? We shall learn how to construct the feed line, how to make a graphical estimation of the ideal number of stages in a distillation column, then we shall see how to locate the feed point and the effect of the reflux ratio.

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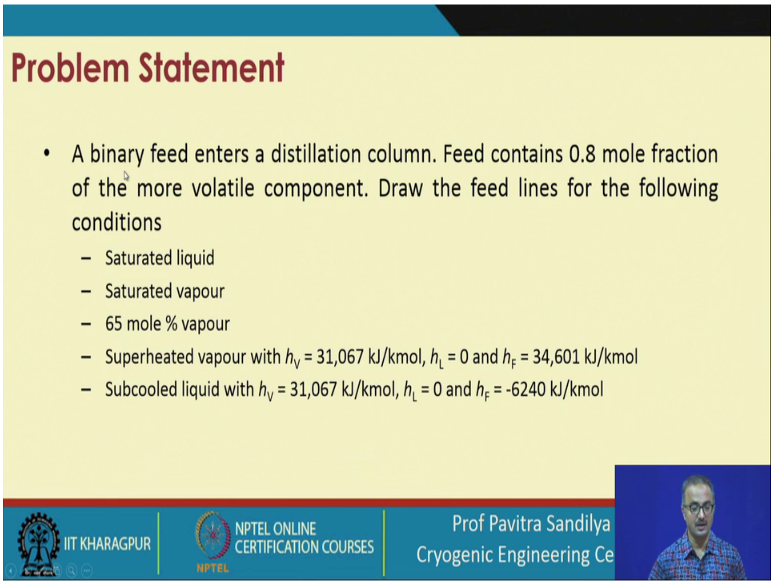

So, first let us go with this problem of drawing the feed lines. Here, we have that a binary feed enters a distillation column and this feed has 0.8 mole fraction of the more volatile component. Now, please understand that to draw the feed line there is no necessity to know the exact the nature of the component; it is enough to know the composition of the component. So, in this particular problem the no component has been mentioned.

Now, we have been asked to draw the feed lines for the following conditions that is for saturated liquid, saturated vapor and some mixture in which we have 65 mole percent of vapor and rest is liquid and superheated vapor and sub cooled liquid for these last 2 conditions, the vapor enthalpy, the liquid enthalpy and the feed enthalpy have been given. Please note that in this case, the liquid enthalpy has taken to be 0 and as you know that enthalpy can be taken to be 0 for any kind of datum. So, whatever enthalpies have been reported in this problem, they have been reported in respect to the this liquid enthalpy.

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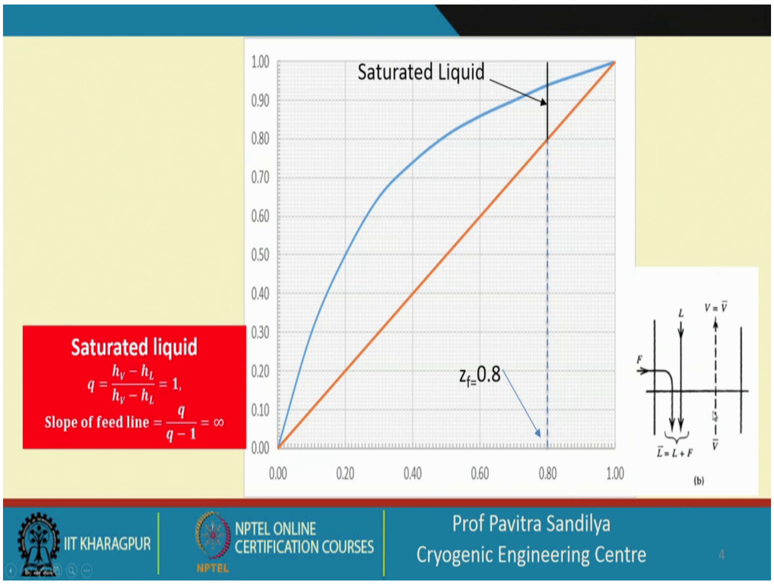

So, now let us go to draw these things. So, here first, we do that we take this particular graph in which on the x axis, we have the liquid side mole fraction and on the y axis, we have the vapor side mole fraction, then we draw this 45 degree line and by some given data, we have some typical equilibrium curve here ok.

Now, after this we locate the feed point and it is given that 0.8 and please note that we are drawing all the mole fractions with respect to the higher volatile component. So, here we locate the feed point and then we go to this 45 degree line where we know that the feed line will pass through Z f; Z f. So, that is how this particular point has been located on the 45 degree line.

And now coming to the saturated liquid we go by the q value and q for q, we know that it is h V minus h L. Now in this case because of feed is saturated. So, its enthalpy is same as that of the saturated liquid. So, we have replaced h F with h L. So, that is how we get that q is equal to 1 and the slope of the feed line is now q by q minus 1.

We put the value of q here and we get that it is infinity what infinity means that it means that we have a straight vertical line. And here in this particular figure we have shown that how the feed introduction will look like that we are putting the feed here with it is only liquid and this liquid is coming from the rectification section and the vapor is going from the stripping to the rectification section.

Now, what we find the introduction of feed because it is liquid it is going to increase the liquid flow rate in the stripping section by adding to the liquid flow rate from the enriching section. So, that is how we find that the liquid flow rate in the stripping section is more than the liquid flow rate in the enriching section, whereas, the vapor flow rate in the two sections remain the same.

Now, we go to the saturated vapor, in this case, we replace the feed enthalpy by the saturated vapor enthalpy h V and we find the q value comes to 0 and the slope of the feed line now comes to 0.

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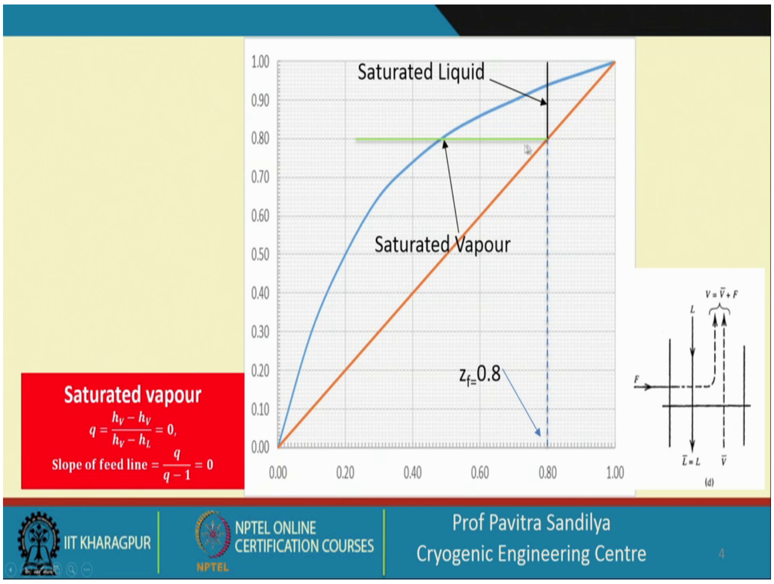

It means that we are going to have a horizontal straight line for the saturated vapor and we see in this particular diagram that the feed is a vapor only. So, it is going to add to the vapor flow rate coming from the stripping section so that the vapor flow rate in the enriching section is getting increased, whereas, the liquid flow rate remains the same in both the enriching section and the stripping section.

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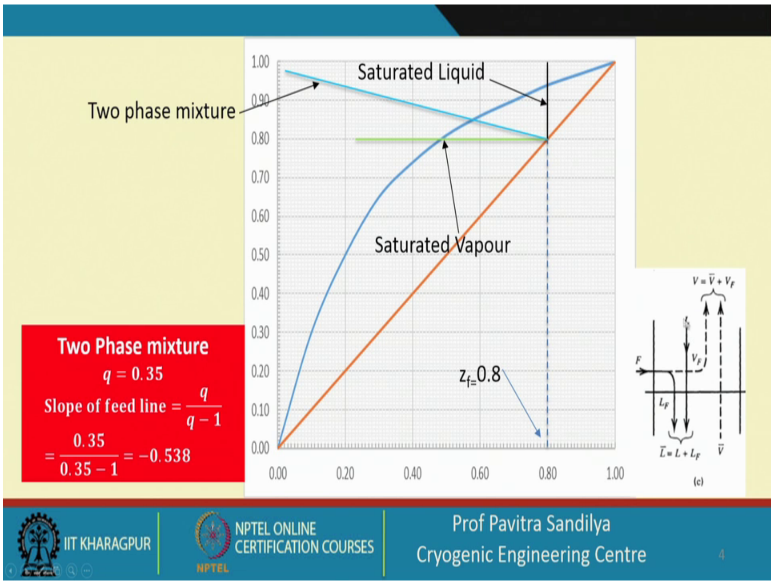

Next we come to the two phase mixture in which we have the q as 0.35 and now the slope of this feed line becomes minus 0.538 and when we plot this one; this gives this particular line with the negative slope. Now what happens that when the feed is the two phase mixture, the vapor will tend to move up and the liquid will tend to move down.

So, in this manner, we find that the vapor flow rate in the enriching section is increased by the amount V F which is coming from the feed and that is how the vapor flow rate in the rectifying section is more than the vapor flow rate in the stripping section. Whereas, the liquid is flowing down so that the liquid flow rate in the stripping section is more than the liquid flow rate in the rectifying section.

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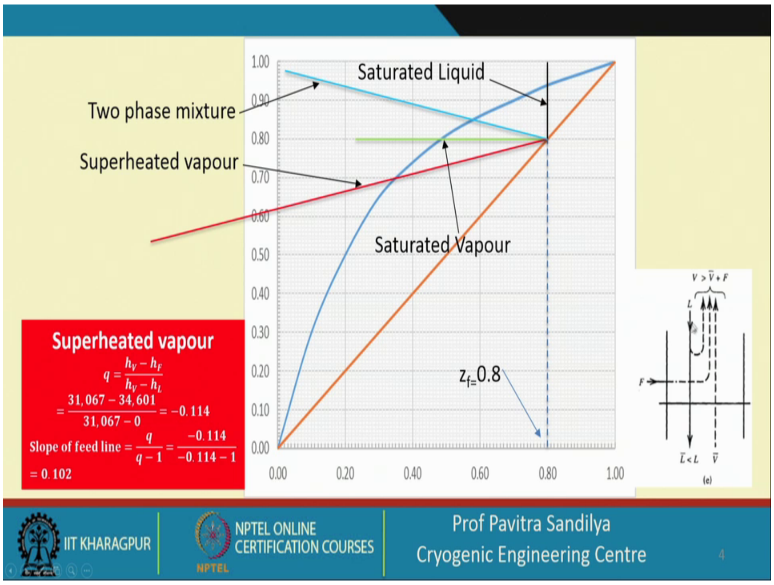

Next we draw it for the superheated vapor, in this case, we keep at the value of h F which is given in the problem and we find it is coming like this minus negative some negative value and now we find the slope is 0.102 and this can be drawn by like this particular line this is the feed line for the superheated vapor.

Now, in this case, what we find that the feed is a superheated vapor. So, when it enters now what happens? It may exchange heat with the liquid which is coming from the rectifying section. So, that a part of the liquid because liquid is already saturated, we assume that in ideal distillation column the liquid is always at its bubble point whereas, the vapor is always at its dew point.

So, when the superheated vapor enters the column what happens some of the liquid get revaporized and it moves up and the it also adds to the vapor flow rate. So, that what we find that the vapor flow rate in the rectifying section becomes more than the summation of the vapor flow rate from the stripping section and the feed flow rate and this more means this additional vapor flow rate is coming from the liquid in the enriching section. And now, we find that the stripping section is having a liquid flow rate which is less than that in the enriching section.

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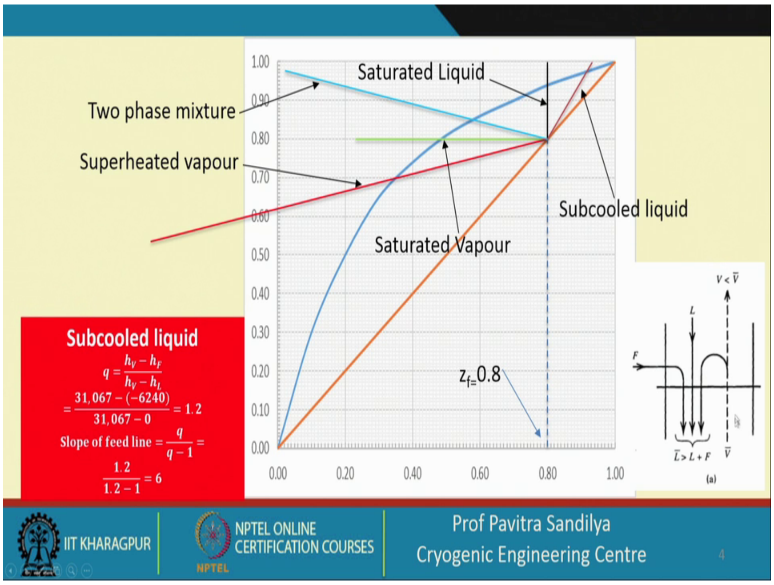

Next, we come to the sub cooled liquid, here, we plug in the value of the h F which is given and we find this is the value of q and from this we find the slope is this 6 and this is this particular line which is representing the sub cooled liquid. Now in this case, we find that the feed is a sub cooled liquid; that means, what will happen that a part of the vapor which is coming from the stripping section which is already at this dew point may get reliquefied and it will go back into the stripping section.

So, that the liquid flow rate in the stripping section is more than the summation of the liquid flow rate from the enriching section and the feed flow rate and the difference is the amount which is getting liquefied from the vapor of the stripping section, whereas, the vapor flow rate in the rectifying section is less than that of the stripping section because some of these vapors have been reliquefied. So, that is how we find that depending on the feed condition how the liquid and the vapor flow rates in the stripping section and the enriching section change with respect to each other.

And how so here we find that the how the feed lines have been located that the this straight vertical line is for sub cooled liquid on the right hand side, we shall be having the sub cooled liquid and the horizontal line is the saturated vapor and between saturated vapor and saturated liquid, we shall be having the vapor liquid mixture, whereas, on the bottom of this saturated vapor line we shall be having the superheated vapor.

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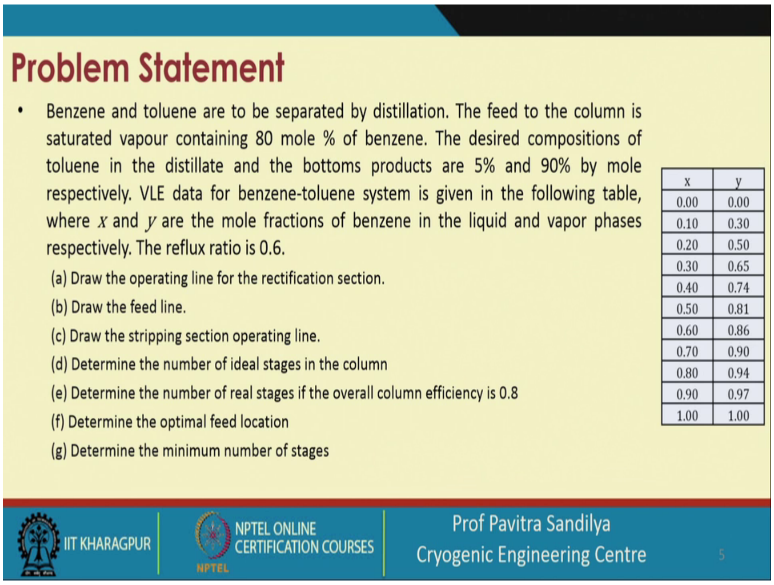

So, this is how we draw the feed line for any distillation column. Having learned this, now we go to the next problem in which we are going to look at the total distillation column, here we are dealing with a mixture of benzene and toluene which have to be separated by distillation. The feed composition has been given as 80 mole percent of benzene and the desired compositions of the distillate and the bottoms have been given in terms of the toluene. So, we find that in the because between benzene and toluene; benzene is more volatile. So, the distillate will be enriched with benzene whereas, the bottoms will be enriched with toluene.

So, we find that here in the distillate we have 5 percent toluene; that means, 95 percent is the benzene concentration in the distillate, whereas, in the bottom, we have 90 percent toluene that is 5 percent; 10 percent is the mole fraction of benzene in the bottoms. So, and then the vapor liquid equivalent data has been given in this particular table this x represents the mole fraction of benzene in the liquid phase and y represents the mole fraction of benzene in the vapor phase which is in equilibrium with the liquid phase.

And here are the data, reflux ratio have been specified as 0.6; what we have been asked to do to draw the operating line for the rectification section, the feed line, the stripping section. And then we have to determine the number of ideal stages in the column, the number of real stages of the column considering the column efficiency as 0.8, then determine the optimal feed location and lastly to determine the minimum number of ideal stages.

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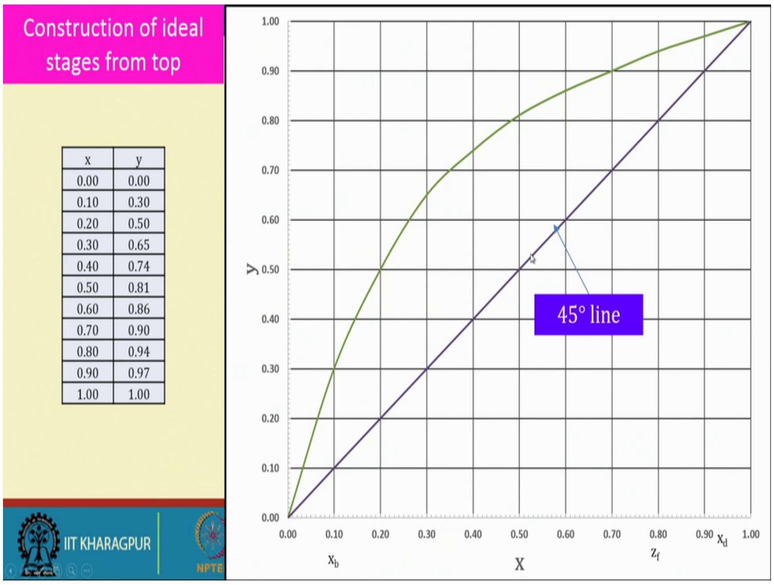

So, here we go with the first part of the problem. First what we do? Using this equilibrium data, we plot this x y diagram, mind it; this x is the mole fraction of benzene and y is the mole fraction of benzene in the vapor phase. Now after locating this do, then we draw the 45 degree line.

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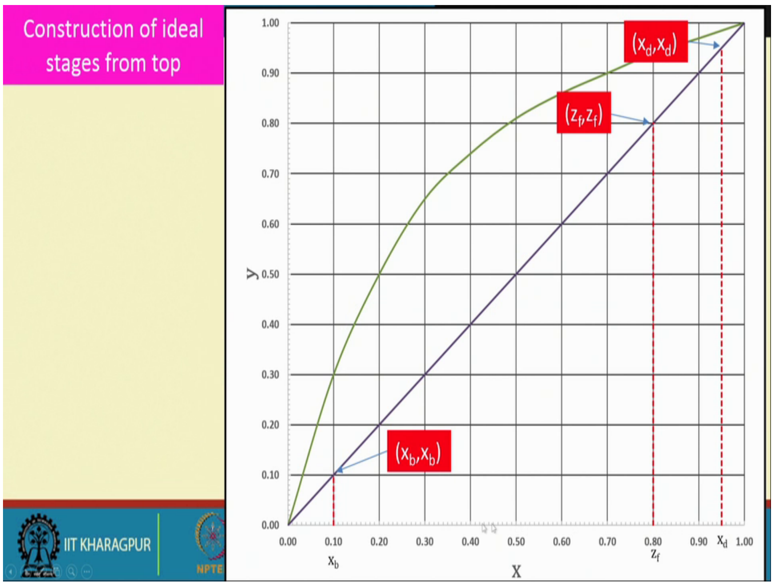

And then we locate the various points given that is this is the X d, X d, X d, this is the Z f and this is the X b.

Now, we know that all these three points will be lying on the 45 degree line for the rectification section it will be X d; X d for the feed line Z f; Z f is one point and for the operating line for the stripping section X b; X b is one point on the operating line. So, first we locate the three points which will be lying on the 2 operating lines and the feed line after that we have to consider the equation for the operating line of the rectification section.

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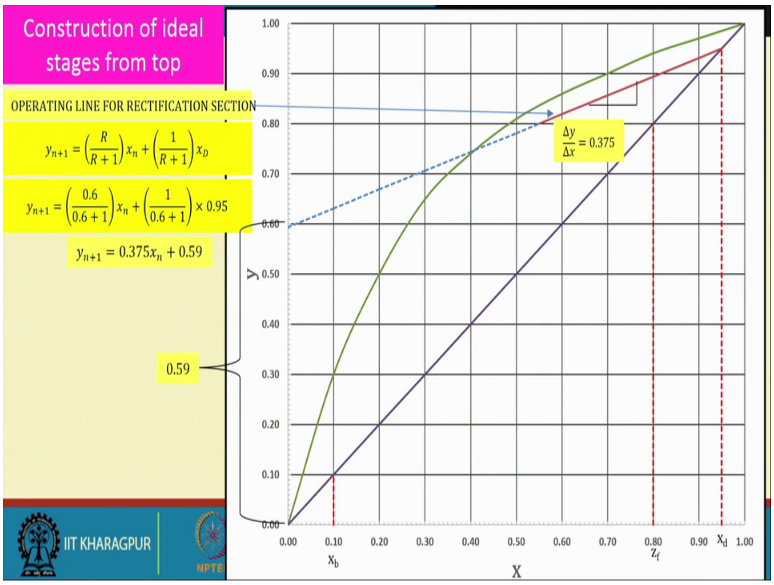

Here we find that we this is given in terms of reflux ratio we plug in the value of the reflux ratio as 0.6 and we get this as the operating line equation.

Now, that means, we know that it is passing through X d; X d and it will have a slope of 0.375 either I do y slope or what we can do we can take the y intercept and these have been shown in the figure. Now that this is the y intercept, this is 0.59 or we can go by the slope. So, I can use either the intercept or the slope to draw the operating line from point X d X d.

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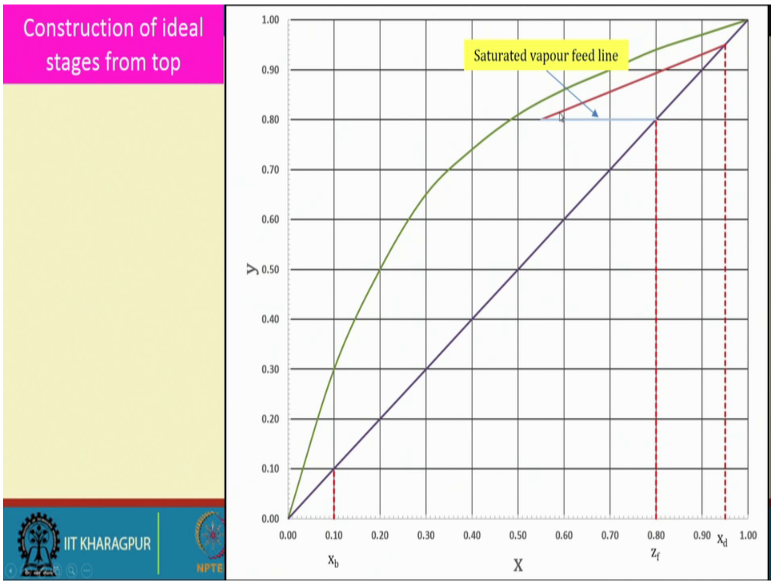

After drawing the operating line for the rectifying section what we do we draw the feed line and because it is saturated vapor. So, here we are drawing the horizontal line for the feed and once we know the intersection between the operating line of the rectifying section and the feed line from this point of intersection we simply join the X b X b point to get the operating line of the stripping section.

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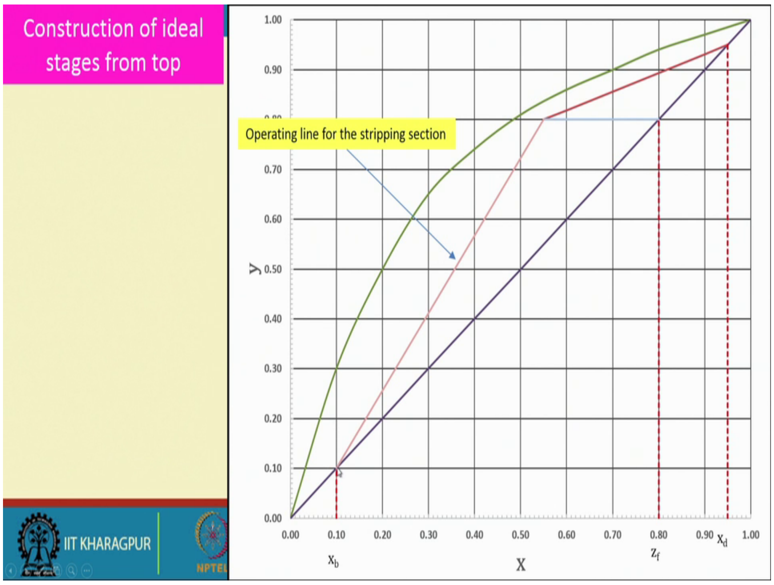

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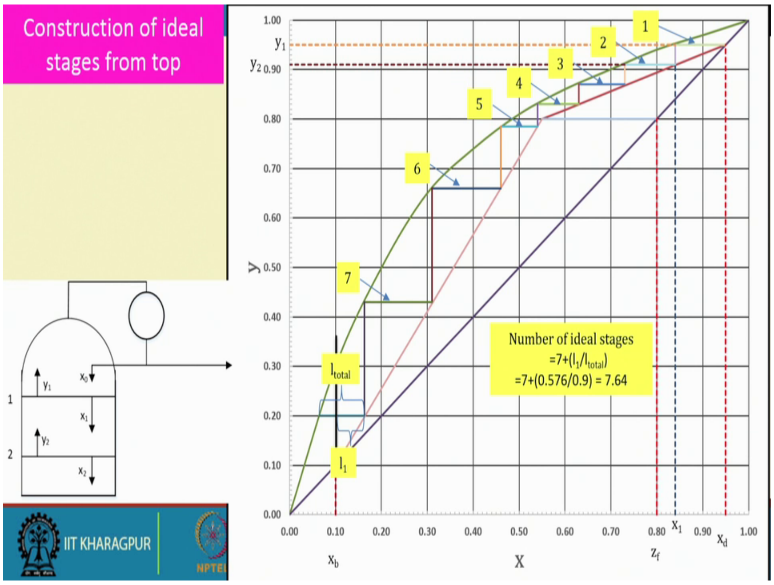

Now, let us move on to construct the i number of stages through the staircase construction about which we learnt in the theory. Now here first, we see that how this column looks like that here the vapor is coming out from the column with the composition of y 1, it is getting condensed and in this case, this condensation may be partial or may be total. So, after condensation we are getting this as the X d and from here we get the x 0 as the liquid concentration of the reflux.

Now, from the stage 1 we are getting the x 1 from stage 2, we are getting x 2 and all these x and y are given in terms of the benzene concentration. So, first after this is what we find that we go to this particular equilibrium curve. So, to know suppose if this particular x 0 and x 0, if this total condenser then x 0 will be same as y 1. So, that is how we can say that and y 1 is in equilibrium with x 1. So, if I can find y 1; that means, this X d X d X d x 0 and y 1, they have the same composition in case of a total condenser. Now once we find x 0 or x 0 or y 1 from that; we can go to the equilibrium curve that is why we have drawn this horizontal line and from there, we get the value of this x 1.

Now, once I know x 1, what we will do we go to the operating line equation to find the value of y 2. So, what we do from this x 1, we draw a vertical which is just touching this operating line of the rectifying section and this point where it touches the operating line is the value of y 2 and once, we get the value of y 2, then we go to the equilibrium curve to get the value of x 2.

So, that is how we find that here when this particular point has been taken to the equilibrium curve, this is representing the value of the x 2; that means, what that whenever we are drawing any horizontal line it represents a particular stage because it horizontal line is relating the outgoing streams. So, that is how this is one stage and this is another stage and similar manner we keep on constructing this stair staircase by considering the equilibrium curve and the operating line alternately and we find that we are able to draw these staircases one by one and until we reach the X b that is the composition at the of the benzene at the stripping section. Now here we stop our construction.

Now, what we find that this particular thing is when the horizontal line is crossing is crossing the required bottoms composition; that means, we do not need a full stage please understand that a stage can be a fraction it need not be whole number. So, we can have a fraction of a stage and whenever you are constructing these lines for your clarity, we have drawn with thicker lines, but please understand these lines have to be drawn very carefully and you have to make perfect horizontal lines and perfect vertical lines with very sharp edged pencil. Otherwise, you are going to miss locate all these intersection points and if there is any kind of miss location of the points you will find you will get wrong values of the number of stages. So, you have to be very very careful in drawing these lines.

Now, once we have drawn the staircases what we now do we simply count the number of horizontal lines from the top 1, 2, 3, 4, 5, 6 and 7 and this is not 8 because this is though this one is not fully utilized for reaching the desired concentration. So, what we do? We try to find out that how much is needed to reach this particular composition. So, we put a vertical line, then we see we just be the scale we can measure the length of this whole line and we can measure this particular length which is up to the given bottoms composition.

So, this particular fraction of the total this total represents one stage, but we need only a fraction of the total stage. So, what we do we measure these 2 lines or we can measure this particular composition given by this particular length and we find that we are giving getting this number of ideal stage at 7.64. So, please understand that we are getting the number of ideal stages in fraction and this is not to be confused with actual number of trays which will always be whole number.

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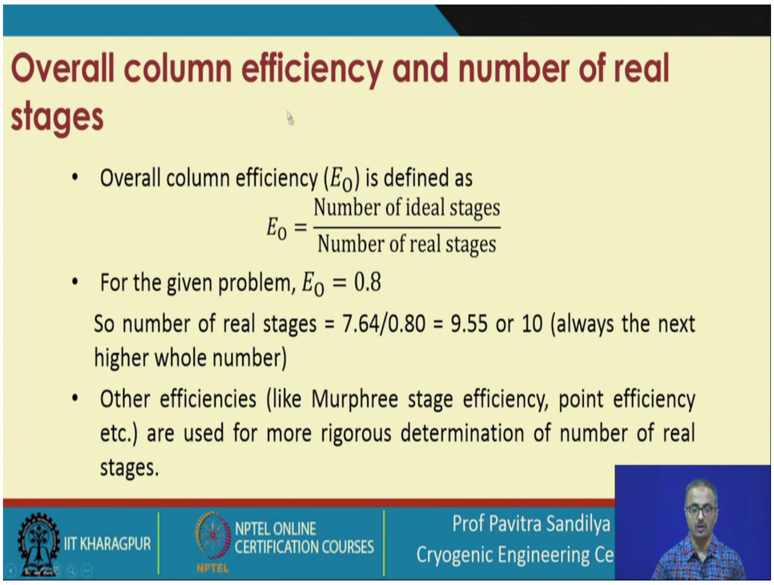

Now to know the actual number of trays; what we do we define some kind of column efficiency, there we have the overall column efficiency we define these as the ratio of the number of ideal stages to the number of real stages, the number of real stages for a given separation will always be more than the number of ideal stages. And now, in the problem this overall efficiency has been given to be 0.8. So, from this we get the number of real stages as 9.55. Now 9.55; this is fraction this cannot be a real life solution. So, what we do we say that we have the actual number is the next higher whole number that is 10; that means, any fraction between 9 and 10 will be taken as 10 as the real number of trays.

Now, this is one of the ways to account for the non ideality of the stages, there are other detailed analysis which are given by this Murphree stage efficiency point efficiency etcetera which are not to be taught under this particular course.

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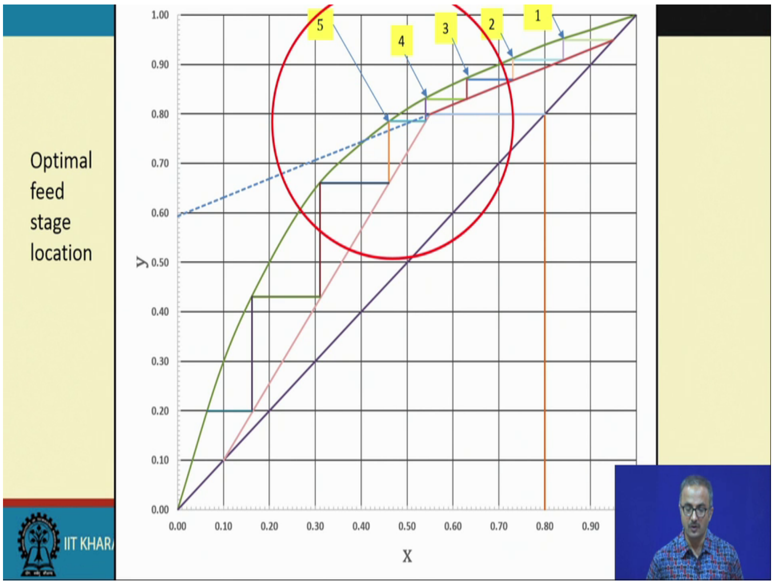

Now, we go the to the optimal feed location, what we see that in this particular thing that whenever we are constructing this staircases whenever we are crossing the feed point, this is a feed point we are also changing the operating line. First, we up to the feed point, we were using the operating line in the rectifying section and once you have crossed the feed point we have, we are using the operating line for the stripping section and this is done to keep the number of ideal stages minimum.

Now, when we want to know that at what point; that means, the feed has been introduced somewhere here. So, what we do to get this the location of this what we do that we are zooming this part and we see that this particular part at this particular point, we are introducing the feed now what we do again we do the same calculation as before.

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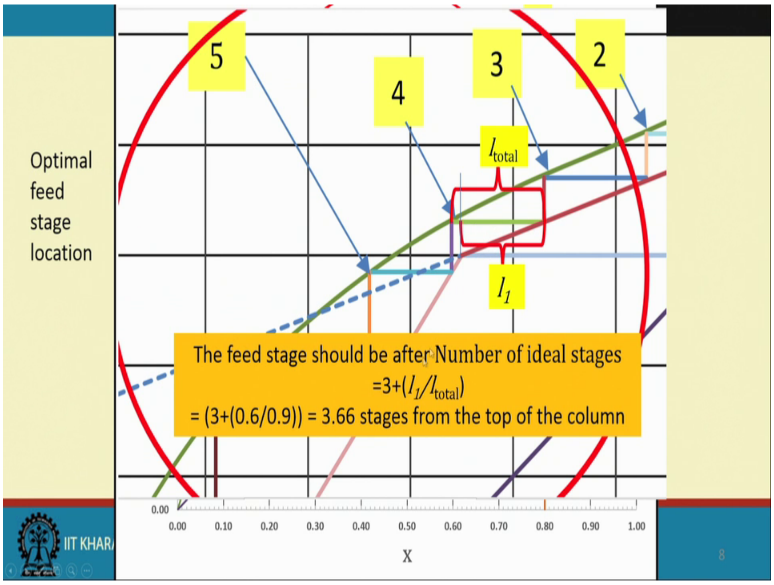

And we find that we find the 2 lengths the total length and this particular length and we get this ratio and what we do that we find that this is 1, 2, 3; these are 3 complete ideal stages plus this fraction that is coming out to be 3.66 stages from the top of the column. So, that is how we locate the feed point for the distillation column.

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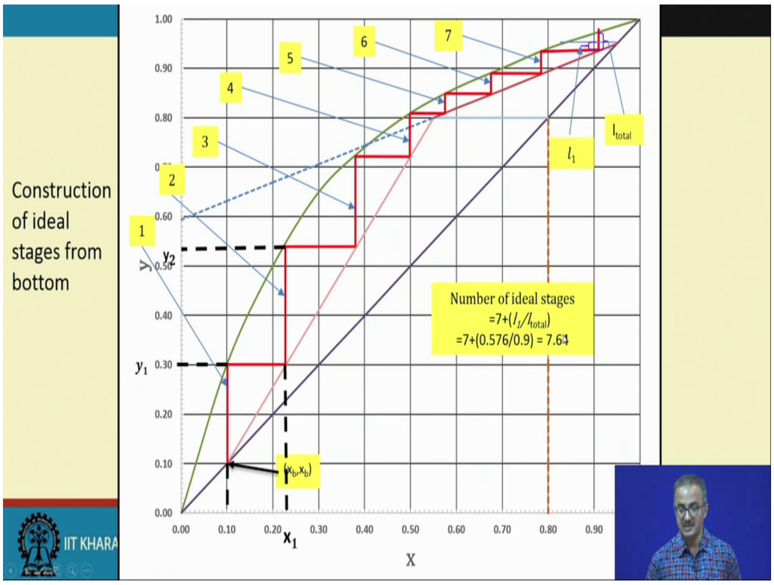

Now, we can repeat the same exercise not from the top, but from the bottom of the column and we should get the same result. Now to get the this staircase construction considering the bottom the stripping section what we do now from stripping section we go to the equilibrium curve because there because the vapor this is this vapor which is coming out from the reboiler, the reboiler is generally taken to be a partial reboiler and ideally the vapor and the liquid will be at equilibrium.

So, what we do that after this x b is taken to be liquid composition of the bottoms. So, the this particular vapor this y 1 represents the vapor which is coming out from the reboiler and this vapor goes into the column and then we can get the composition of the liquid stream which is passing this particular vapor from the reboiler. And that is how we keep on doing this particular staircase construction only thing, you have to mind is in this case, the vertical line is representing one equilibrium stage unlike the horizontal line in case of the stair case construction from the top.

So, to know the ideal number of stages; what we will do? We will just count the vertical lines and here, we find as we are constructing these lines as soon as the vertical is crossing this X d point, we stop our construction. Now to count the number of ideal stages, we what we do we just count this the vertical lines 1, 2, 3, 4, 5, 6, 7 and then again, we make this horizontal this vertical fraction that by making a horizontal line here, we find out this total length and this small length and from this we find we are getting the number of ideal stages at 7.64. That means, we find whether we start the construction from the top or the bottom, it does not matter the number of ideal stages will be the same.

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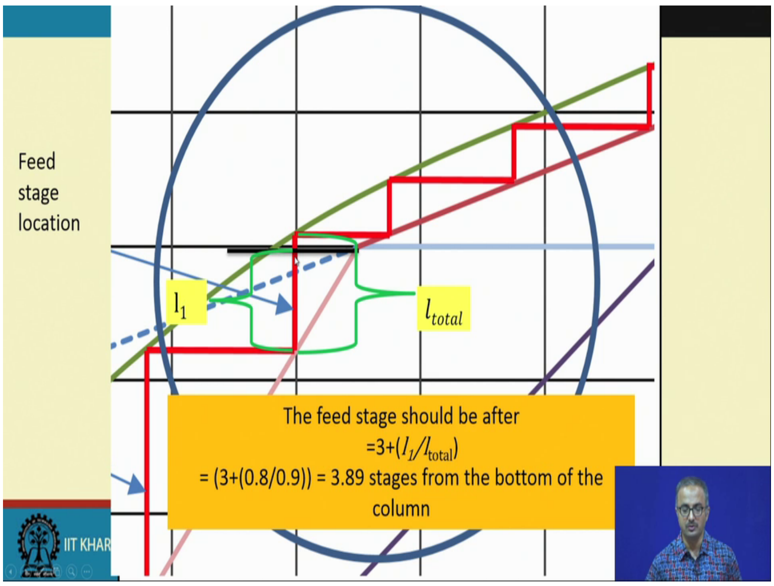

Now, in this case, the feed is located by seeing that whenever this particular vertical is crossing the feed point, we take this fraction this particular fraction from the bottom as the feed point location. So, we measure the total length of the this vertical line and we take this particular length up to this up to the horizontal line which is coming from the feed point and we take this fraction; that means, this fraction is about 3.89 stages from the bottom of the column we are introducing the feed.

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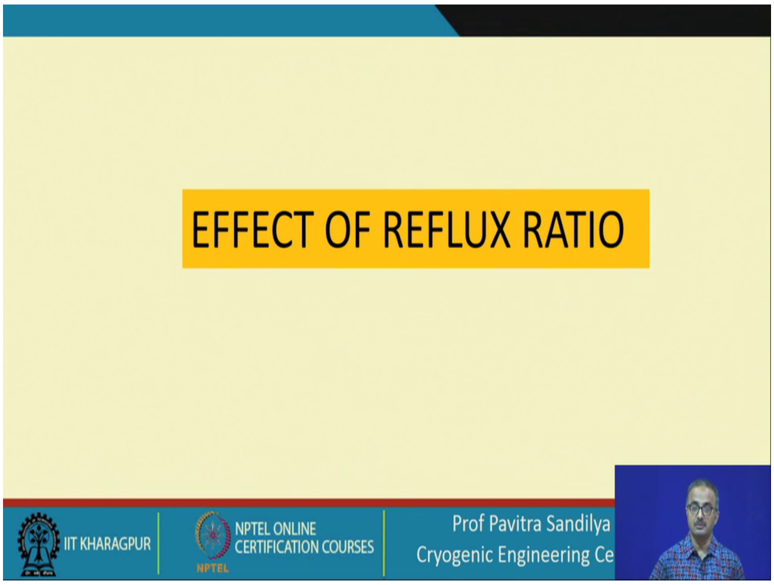

After learning, this construction of the stair cases and to find out the number of ideal stages, next we go to see the effect of the reflux ratio, this is very important because if we change the reflux ratio that will have a direct effect on the condensation. Because of more the condensation the more will be the liquid generation and that we can increase the reflux, but it will also increase the cost of the liquefaction. So, that is why it is very important for us to know the reflux ratio.

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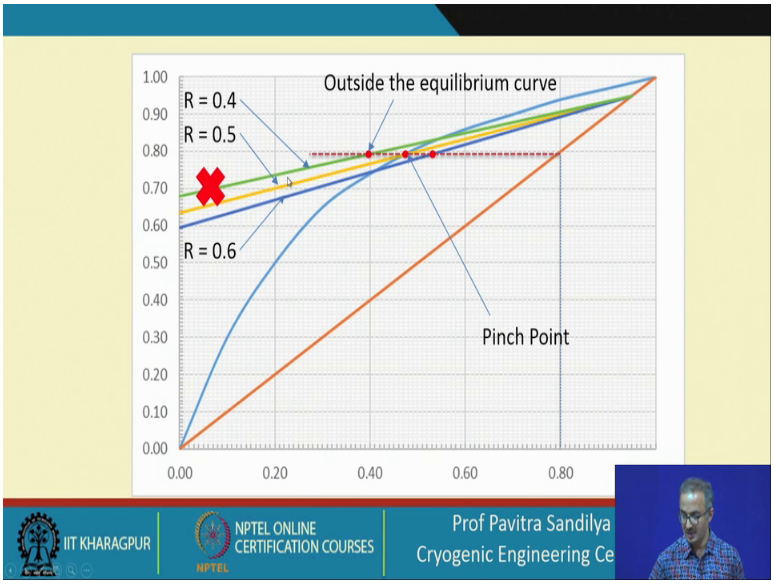

Now, here we find that for three different reflux ratios, we have drawn these operating lines, what we find as we decrease the reflux ratio we find the operating line keeps on moving up and this can be easily seen because the intercept is X d by R plus 1 where if R is increasing. What we find? The X d by R plus 1 is decreasing. So, we find that by decreasing the R, we are increasing the intercept.

So, that the operating line is shifting upward and if we locate the feed line here, again, what we find that for this particular reflux ratio 0.6, this intersection is below this particular equilibrium curve, but when it is about 0.5, we find that this point of intersection is just on the equilibrium curve and when we see the intersection for the this 0.4, it is find that this intersection is going out.

Now, we have to understand that this particular point where the feed line, the operating line and the equilibrium curve are intersecting this is called the pinch point. Pinch point means here we are finding there is no difference between the operating line and equilibrium curve. So, whenever we are constructing the staircases, we find that we will not be able to cross this point because it has pinched. So, we say that in this case the number of stages becomes infinity, whereas, this particular point is not admissible because this shows the actual separation is going above the equilibrium separation which is not possible thermodynamically that is this particular reflux ratio is ruled out.

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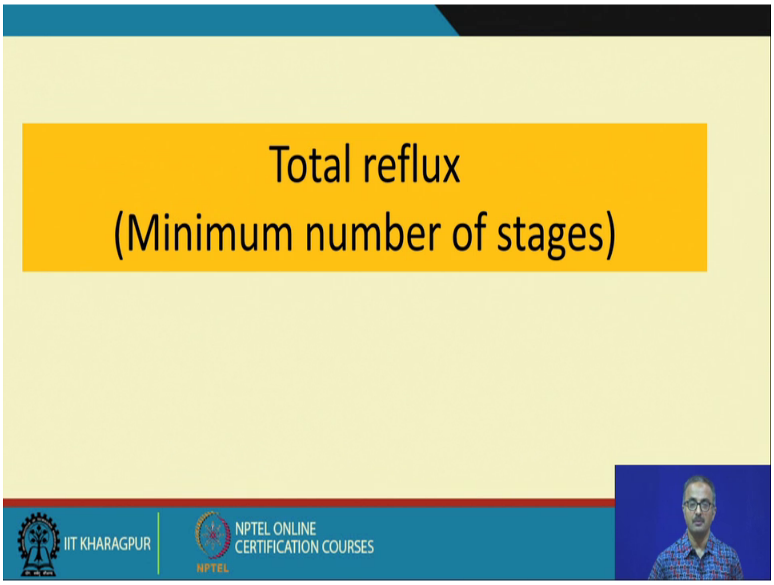

So, here we see the effect of the reflux ratio and lastly we see the total reflux what happens a total reflux and in this case we get the minimum number of stages and we will see how.

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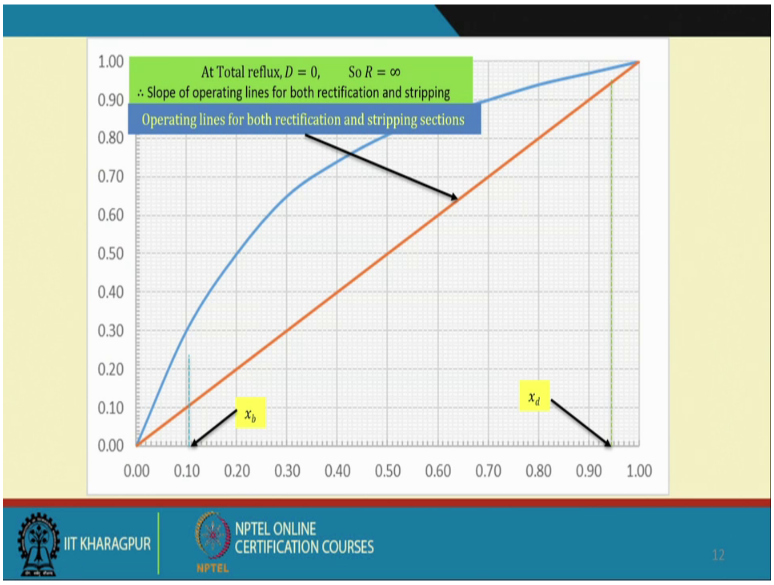

When we talk of total reflux it means that all the liquid that is coming from the condenser is sent back to the column and we are not withdrawing any distillate. So, that the distillate flow rate is 0 and the reflux ratio which is the ratio of the reflux liquid to the distillate flow rate becomes infinity. The reflex ratio is infinity means what that this operating line for the both rectifying section and the stripping section are merging with the 45 degree line.

So, when this happens this 45 line. So, what we find that now with this we can because now that we have taken D as 0. Now we cannot have any further change in the distillate that is the extreme, we can go to right. So, what we do that in this case, the D is list and when we have list D and because the operating line has now taken the position at the lower most point as a 45 degree line. So, we say that in this case we shall be getting the minimum number of stages.

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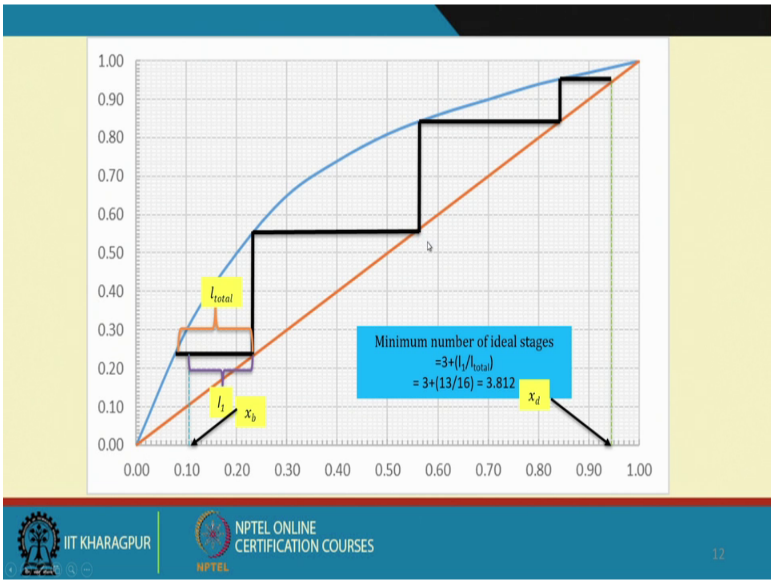

And when we start constructing these staircases whatever value we get here now from this we can find that this is 1, 2, 3 and some fraction over here and this fraction is coming out to be a 0.812. That means, the minimum number of ideal stages is found to be 3.812 which happens when we have total reflux that is when we do not withdraw the distillate and this kind of situation comes when we are starting of the distillation unit because maybe we do not have both the liquid and vapor phases flowing.

So, we need to generate these enough of this liquid and vapor phases to during that time, we do not withdraw any distillate and when you do not withdraw any distillate, we also do not withdraw any bottoms and we also stop the feed. So, without any feed without any distillation without any bottom we run this particular column under the total reflux condition and in that case, we get the minimum number of ideal stages. So, these are the books which you can refer to for further detail.

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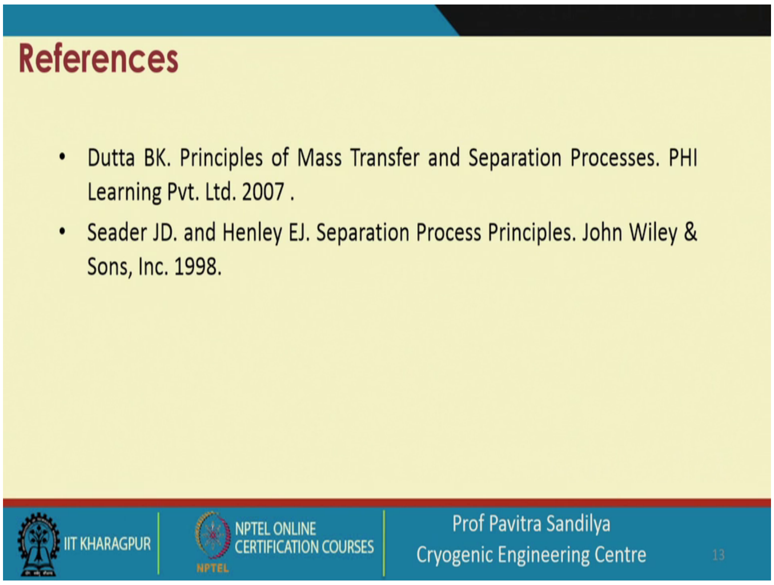

Thank you.